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A Computational Analysis of a Shear Punch Test

by Stephan R. Bilyk

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The intense shearing that occurs in propellants and explosives during impulsive loading can lead to initiation. In an effort to determine useful shear initiation criteria, the U.S. Army Research Laboratory (ARL) has developed a shear punch test using a modified Kolsky bar. Varying the striker bar's velocity and length controls the shear rate and duration. Shear velocities approaching 100 m/s and durations as long as 200 µs are possible. Experimental results have been obtained for several energetic materials and a nonreacting polymer, polycarbonate (PC). This report presents a detailed computational analysis of the shear punch test using the Arbitrary-Lagrangian-Eulerian code ALEGRA. The inert PC was selected for this preliminary study since a more complete set of dynamic property data is available for this material. The validity of a conventional viscoplastic constitutive relation and the failure criterion for PC is determined based on their ability to predict the observed mechanical response. An alternative viscoelastic-plastic model is presented for improving the predicted material response.					
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A COMPUTATIONAL ANALYSIS OF A SHEAR PUNCH TEST

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The intense shearing that occurs in propellants and explosives during impulsive loading can lead to initiation. In an effort to determine useful shear initiation criteria, the U.S. Army Research Laboratory (ARL) has developed a shear punch test using a modified Kolsky bar. Varying the striker bar's velocity and length controls the shear rate and duration. Shear velocities approaching 100 m/s and durations as long as 200 μ s are possible. Experimental results have been obtained for several energetic materials and a nonreacting polymer, polycarbonate (PC). This paper presents a detailed computational analysis of the shear punch test using the Arbitrary-Lagrangian-Eulerian code ALEGRA. The inert PC was selected for this preliminary study since a more complete set of dynamic property data is available for this material. The validity of a conventional viscoplastic constitutive relation and the failure criterion for PC is determined based on their ability to predict the observed mechanical response. An alternative viscoelastic-plastic model is presented for improving the predicted material response.

INTRODUCTION

Energetic materials are often ranked in terms of their sensitivity when subjected to shock, shear, and thermal stimuli. The goal for military applications is to develop initiation criteria under each stimuli as well as a fundamental understanding of coupled behavior. Several useful analytical models and experiments already exist for shock and thermal stimuli. However, initiation due to shear loading is complex and poorly understood. Many hazardous scenarios such as penetrator fragments or shrapnel impacting an explosive canister can lead to shear initiation of an energetic. Shear initiation

occurs at timescales over tens or hundreds of microseconds, an order of magnitude larger than shock loading. Energy is deposited in localized regions causing a local temperature rise, which for some energetics can even lead to the development of adiabatic shear bands.

Initially, the activator punch test was developed to study shear initiation [1]. This test was limited since it was difficult to control the shear velocity independently of the pressure and the pressure on the shear surface was not well known. Recently, Krzewinski, *et al.* [2] developed a shear punch test at ARL. The shear punch test uses a modified Kolsky bar technique and obtains data for shear initiation of energetic materials

subjected to dynamic loading conditions. In addition, some non-energetic polymer materials such as polycarbonate (PC) have been used as specimens for comparison purposes.

Numerical modeling of this test is difficult because it requires a mesh formulation that can withstand severe deformation and an ignition model that includes shear loading and friction effects. In a pure Eulerian formulation, the material moves through a static mesh. Although a pure Eulerian formulation is not appropriate to study wave propagation, it is attractive because it can handle severe deformations. However, the material advection algorithm tends to "smear" the deformation over a number of cells leading to an unrealistic deformation. Further refinement of the mesh does not resolve material advection and creates an unreasonably large mesh for the computer processors.

In a pure Lagrangian formulation, the mesh moves with the material. This formulation adequately describes the wave propagation but cannot handle the severe deformations of the specimen in a dynamic punch test. For this reason, an alternative formulation called an arbitrary-Lagrangian-Eulerian (ALE) method was chosen. The ALE method starts out Lagrangian until severe deformations are triggered. At this time the Lagrangian formulation pauses to allow for some material advection and re-meshing, then returns to a Lagrangian formulation for the next time step. The advantage is that numerical dissipation is avoided until large deformations occur and then is limited to only those regions where there are severe mesh distortions and the mesh must be removed. The general name for the ALE method is adaptive mesh

refinement since the mesh adapts to the materials loading environment.

This paper first establishes an effective numerical modeling approach of the shear punch test. As an initial approach we chose to neglect the energetic properties of the material and focus on modeling the entire experiment with the severe deformations of the specimen. For this reason, the results discussed are for a PC specimen.

EXPERIMENTAL DESCRIPTION

The apparatus used for the shear punch test was a modified Kolsky bar, as shown in Figure 1. The striker, incident, and output bars were 1.27cm diameter 350-maraging steel. The incident and output bars were 150cm in length, while the striker bar was available in 25, 50, and 55cm lengths. The varying striker lengths gave nominal pulse durations of 100, 200, and 220 μ s, respectively [2]. The specimen had a diameter of 1.905cm and a length of 1.27cm.

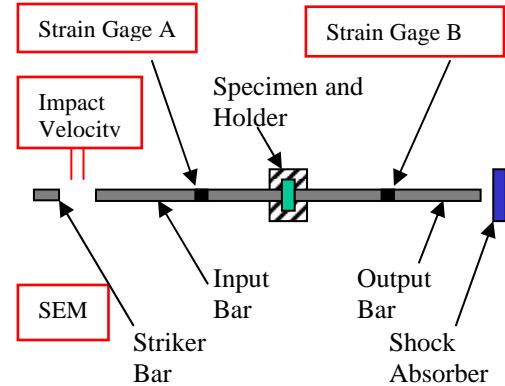


Figure 1. Schematic of Shear Punch Test and data collection (Not to Scale).

The experimental measurements are also shown (boxed) in Figure 1. Impact velocity was measured using three fiber optic wires and an optical detector. Two strain gages were mounted near the center of the input and output

bars to measure the incident, reflected, and transmitted strains. Finally, a scanning electron microscope (SEM) was used to measure the punch and dent displacements of the specimen as well as examine any fracture regions.

A special shock absorber and transfer piston (not shown in Figure 1) were designed to prevent reverse bar motion whenever the specimen reacted violently. Thin polyethylene disks were also placed between the specimen and incident/output bars for impedance matching. A copper (3mil) and Kaptan (5mil) disk were between the striker and incident bar to reduce ringing and wave shape the incident compressive pulse. The specimen holder was made from 17-4 PH stainless steel and consisted of three pieces held together with six high-strength bolts. In addition, vacuum grease was applied between the specimen and specimen holder to fill any voids and reduce friction at the interfaces. With the applied grease, one can conclude that all initiations occurred because of the shearing within the specimen.

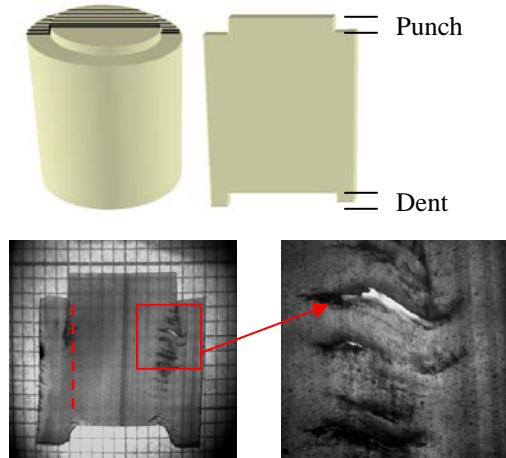


Figure 2. Typical specimen deformation and idealized shear surface (dotted line).

A typical deformed specimen shape is shown in Figure 2. The specimen shown is a double-base propellant, P1. Note also in Figure 2, that the shear surface has localized and runs along the outer radial edges of the incident bar. For this dynamic test, the loading on the P1 specimen was great enough to eventually fracture the specimen along the shear surface.

NUMERICAL DESCRIPTION

The hydrocode ALEGRA was used for the numerical simulations [3]. ALEGRA is an arbitrary Lagrangian-Eulerian finite element code developed by Sandia National Laboratories that emphasizes large distortion and shock propagation. It has been designed to run on distributed-memory parallel computers to reduce the large memory requirements for some problems.

The entire computational domain included the incident and output bars, the specimen, and the specimen holder. For the simulation presented, the 50cm striker bar was replaced with a prescribed input velocity boundary condition on the end nodes of the incident bar. The z-velocity pulse had a 1300m/s material velocity, a 5 μ s rise time with a duration of 200 μ s, as shown in Figure 3.

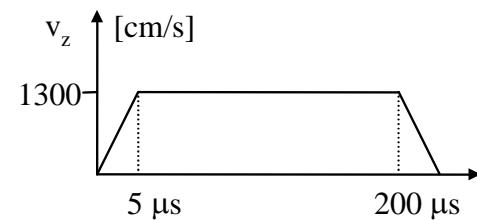


Figure 3. The prescribed z-velocity boundary condition on the end nodes of the input bar.

To take advantage of the symmetry, an axisymmetric hybrid computational domain was built using quad cells. The input bar, output bar, and specimen holder had a Lagrangian mesh and the specimen was described with an ALE mesh, as shown in Figure 4. The compression wave reaches the specimen at approximately 300 μ s after the start of the problem.

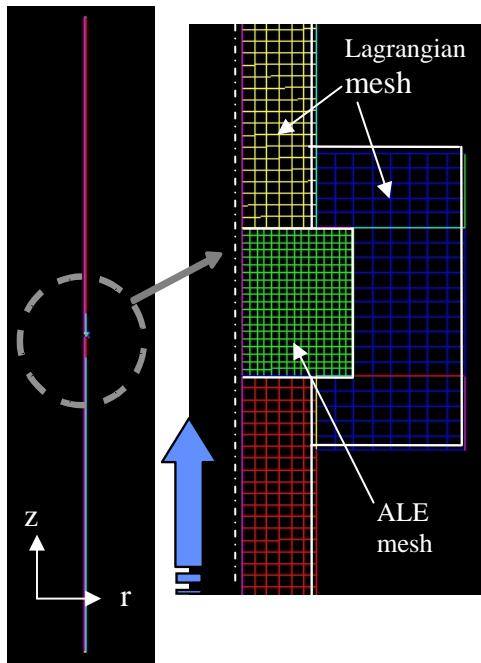


Figure 4. The computational domain for the shear punch test and a close-up of the specimen region.

Contact surfaces were added between the incident/output bars and specimen as well as the specimen and holder piece to prevent artificial node penetration. Careful mesh refinement must be exercised for the specimen. As the compression wave reflects off the sides of the holder, the specimen surface near the holder interface goes into tension. If the holder nodes are much more massive than the specimen, a large amount of momentum is transferred to

the specimen and can cause the specimen node to jump back or hourglass (see Figure 5). Refining the holder mesh with the specimen, thereby reducing the mass of the holder node, can prevent this hourgassing.

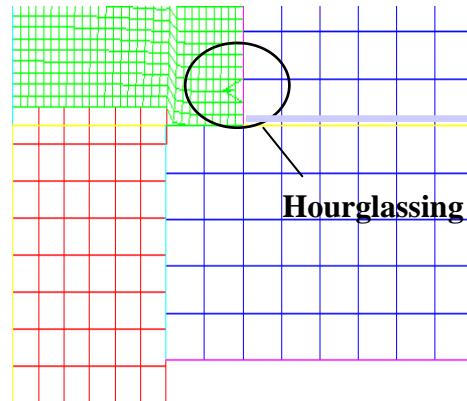


Figure 5. Numerical challenge encountered during specimen mesh refinement.

For the initial simulations discussed, we chose to neglect the ignition of the specimen. The specimen modeled was the polymer material, polycarbonate. The incident bar, output bar, and specimen holder were modeled using a classic elastic-plastic constitutive model. This model uses a generalized Hooke's Law for the elastic stress-strain response, von Mises yield criteria, isotropic hardening, and simple radial return [4]. For the PC specimen, the Johnson-Cook viscoplastic model was used. In this model the yield stress is dependent on temperature, rate of deformation, and strain [5]. In addition, the pressure dependent fracture model was used for the PC specimen [6]. This model uses void insertion and is triggered when the pressure in the material element is less than the fracture pressure. The fracture pressure used was -80MPa. The specific material parameters used for the constitutive

models are given in Tables 1a and 1b. In Table 1a, ν is Poissons ratio, Y is Youngs modulus, σ_{yield} is the yield stress, and E_n is the hardening modulus. In Table 1b, A is the yield stress, B and n are strain hardening parameters, C is the rate sensitivity parameter, and m is the thermal softening parameter.

Table 1. Material constants used for the constitutive models.

(a) Elastic-Plastic Model

Material	Y [GPa]	ν	σ_{yield} [MPa]	E_n [MPa]
Maraging steel	199	0.33	2242	0.00
Stainless steel	200	0.33	1170	100

(b) Johnson-Cook Model

	A [MPa]	B [MPa]	C	m	n
PC	759	69	0.00	1.85	1.00

RESULTS AND DISCUSSION

A plot of the deformed mesh for the specimen is shown in Figure 6. Approximately 25,000 elements were used for incident bar, output bar, holder, and specimen. The specimen had approximately 1250 elements with a mesh resolution of 0.032cm/element. In Figure 6, note the shearing surface formed in the specimen. The profile of the shear surface resembles a rose petal. This shear profile is due to the right angle in the input bar. It becomes a straight line profile when we add a small curvature to input bar end.

A comparison of the strain gage signals to the observed result shows excellent agreement, as shown in Figures 7a and 7b. The incident and reflected pulses are shown in Figure 7a. The small difference in magnitude for

the incident pulse occurs because the experimental impact velocity was 27.61m/s compared with 26.0m/s used in the simulation. The curvature at the

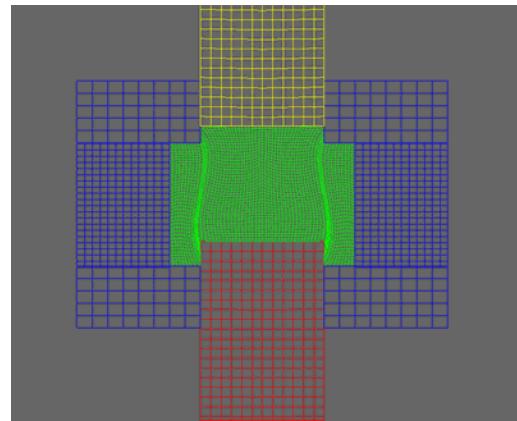


Figure 6. Final shape of the deformed mesh in the specimen.

beginning of the experimental input pulse is due to wave shapers added in front of the input bar. There were no wave shapers added in the numerical simulation. The ringing seen at the beginning and end of the numerical incident signal are due to the sharp discontinuity of the prescribed velocity boundary condition (see Figure 3). Smoothing this boundary condition will reduce the ringing.

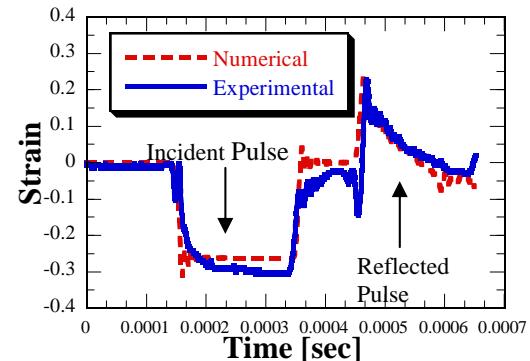


Figure 7a. Comparison of strain signals for incident bar strain gage.

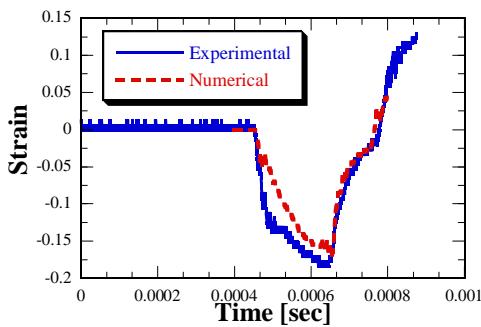


Figure 7b. Comparison of the transmitted strain signal at the output bar.

Figure 8 shows a plot of the specimen temperature at the end of the simulation. PC has a melt temperature of 558 K. The temperature rise is due to the conversion of plastic work to heat. Although the temperature localizes near the bar/specimen interface, it dissipates to neighboring elements because of the mesh resolution. For a finer mesh, the temperature may localize along the idealized shear surface and reach a higher order of magnitude.

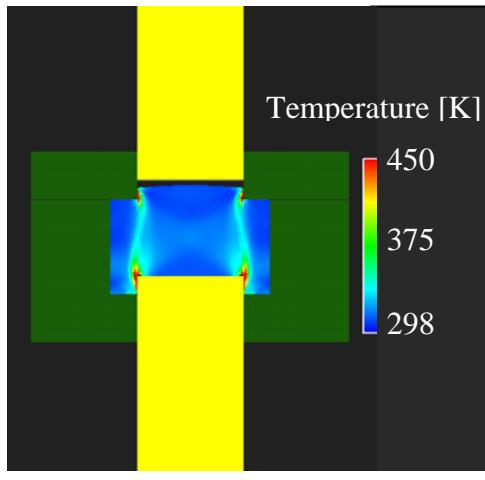


Figure 8. Final temperature rise in the PC specimen.

Figure 9 shows a plot of the specimen's effective strain rate at 420 μ s. At 300 μ s the incident wave has reached the specimen surface. For the plotted time of 420 μ s in Figure 9, the specimen is subjected to compressive loading. The specimen geometry is different from what is required in a standard Kolsky bar. For this reason the strain rate is not uniform in the shear punch specimen. The specimen's strain rate reaches \sim 8000-9000 s^{-1} and localizes along the idealized shear surface.

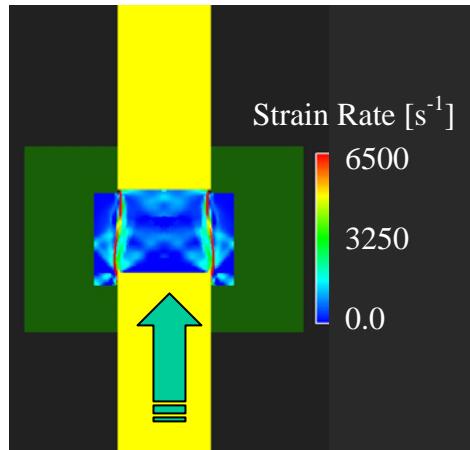


Figure 9. Specimen's strain rate at 420 μ s.

An examination of the shear stress in the specimen during compressive loading at 600 μ s, shows the stresses reach 40-50 MPa (see Figure 10). By comparison the principal compressive stress reaches \sim 150MPa in the center region and \sim 300MPa in the outer region (see Figure 11). Of course, the state of stress will change at the arrival of the transmitted wave. Note that the ALEGRA code considers tensile deviatoric stress and compressive hydrostatic stress as positive. For a finer specimen mesh resolution subjected to this complex state of stress, the specimen material may form adiabatic

shear bands. We also note that the pressure in the PC specimen reaches

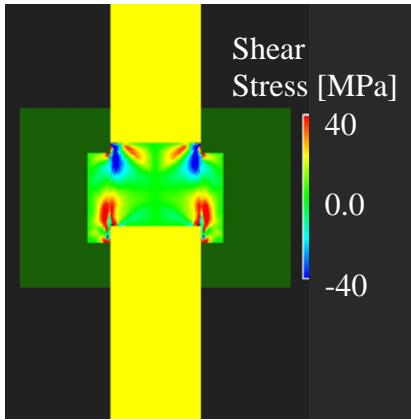


Figure 10. Shear stress in the specimen at $600\mu\text{s}$.

approximately -5 MPa (tensile hydrostatic stress). This pressure is above the fracture pressure (-80 MPa) therefore, the PC specimen did not fracture in this simulation.

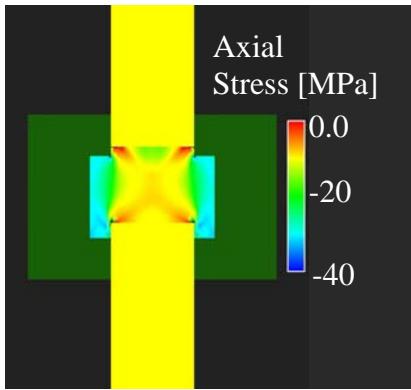


Figure 11. Axial stress in the specimen at $600\mu\text{s}$.

SUMMARY AND OBSERVATIONS

A numerical model of a shear punch test has been developed to study the effects of shear loading on various energetics. To date we have completed

simulations for nonenergetic polymer materials. The simulations showed excellent agreement of the strain gage signals and showed the general trend of an idealized shear surface in the specimen. The hybrid mesh capability in ALEGRA allows complete modeling of the shear punch test. The Lagrangian formulation used for the incident bar, output bar, and specimen holder provides an efficient solution to wave propagation. The ALE mesh for the specimen prevents hourgassing and excessive material advection while maintaining a reasonable timestep. More work is needed to better trigger the remeshing for the specimen.

The prescribed velocity boundary condition eliminates the need to model the striker bar. Smoothing this boundary condition will reduce ringing in the incident strain signal. Also, the mesh was fragmented into segments to provide fast line searching in the contact algorithm.

A clear disadvantage is using the Johnson-Cook (JC) viscoplastic model for the PC specimen. The JC model is normally used to describe rate dependant metal behavior. Polymers and energetic materials show viscoplastic behavior but should not be described as linear elastic. Instead, these materials are viscoelastic where the shear modulus is not constant (asymptotic decay) and a function of strain rate and temperature. Viscoelastic behavior will contribute to the total strain rate and the overall material deformation, even at high rates. Linear elasticity will have no contribution to material deformation. For this reason I installed a viscoelastic-plastic (VEP) model [7] into ALEGRA. The VEP model also uses a plastic flow rule (no yield surface) that is a function of the effective strain, the effective shear

stress, and an effective damage parameter. After the model is tested and verified with experimental comparisons, we will obtain optimized material parameters for PC, PMMA, and for certain energetic materials. Next, VEP will be used as the constitutive model for the specimen in the shear punch simulations. These results will be compared with the present.

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